

ANISOTROPIC SOBOLEV SPACES AND DYNAMICAL TRANSFER OPERATORS: C^∞ FOLIATIONS

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ABSTRACT. We consider a C^∞ Anosov diffeomorphism T with a C^∞ stable dynamical foliation. We show upper bounds on the essential spectral radius of its transfer operator acting on anisotropic Sobolev spaces. (Such bounds are related to the essential decorrelation rate for the SRB measure.) We compare our results to the estimates of Kitaev on the domain of holomorphy of dynamical determinants for differentiable dynamics.

1. INTRODUCTION

Let T be an Anosov diffeomorphism on a d -dimensional compact connected C^∞ Riemann manifold \mathcal{X} (i.e., $T\mathcal{X} = E^u \oplus E^s$ and there are $C > 0$, $\gamma > 1$, with $|DT^n|E^s| \leq C\gamma^{-n}$, $|DT^{-n}|E^u| \leq C\gamma^{-n}$ for all $n \geq 1$). Denote the Jacobian of T with respect to Lebesgue by $|\det DT|$. To construct SRB measures and to analyse their speed of mixing, it is natural to consider the following operators, defined initially on C^∞ functions:

$$(1.1) \quad \mathcal{M}\varphi = \frac{\varphi \circ T^{-1}}{|\det DT| \circ T^{-1}}, \quad \mathcal{L}\varphi = \varphi \circ T.$$

The operator \mathcal{L} fixes the constant functions, while \mathcal{M} fixes the constant functions if and only if $\det DT$ is constant (i.e., if T is volume preserving). The dual of \mathcal{M} restricted to elements of the dual of C^∞ which are finite complex measures, absolutely continuous with respect to Lebesgue with a C^∞ density, coincides with \mathcal{L} viewed as acting on the density and vice-versa. Alternatively, the dual of \mathcal{M} acting on $L^1(\mathcal{X}, \text{Leb})$ is \mathcal{L} acting on $L^\infty(\mathcal{X}, \text{Leb})$.

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For $w \in \mathcal{X}$, and \tilde{T} an Anosov diffeomorphism on \mathcal{X} , introduce local hyperbolicity exponents ($|\cdot|$ denotes euclidean norm)

$$\begin{aligned}\lambda_w(\tilde{T})^{-1} &= \sup_{v \in E^u(\tilde{T}(w)), |v|=1} |D_{T(w)}\tilde{T}^{-1}(v)|, \\ \nu_w(\tilde{T}) &= \sup_{v \in E^s(w), |v|=1} |D_w\tilde{T}(v)|.\end{aligned}$$

Assume T is C^{r+1} for some $r > 0$. Kitaev [14] proved that the following “dynamical Fredholm determinant”

$$d(z) = \exp - \sum_{n=1}^{\infty} \frac{z^n}{n} \sum_{T^n(x)=x} \frac{1}{|\det(DT^n(x) - \text{Id})|}$$

extends to a holomorphic function in each disc $\{z \mid |z| \cdot \rho_1^{(p,s)}(T) < 1\}$, where $p \in (-r, 0)$, $s = r + p$, and

$$\rho_1^{(p,s)}(T) = \lim_{n \rightarrow \infty} \left(\int_{\mathcal{X}} \max((\lambda_w(T^n))^p, (\nu_w(T^n))^s) d\text{Leb}(w) \right)^{1/n} < 1.$$

One may take $s = -p = r/2$: Kitaev’s result is then reminiscent of the “loss of one half of the Hölder exponent” which occurs when going from two-sided subshifts to one-sided subshifts in symbolic dynamics [7], since one easily sees that $\rho_1^{(-r/2,r/2)}(T) \leq \gamma^{-r/2}$.

In view of the results of Ruelle [16] for smooth expanding maps, it is natural to look for Banach spaces $\mathcal{B}_{p,s,\mathcal{L}}$, respectively $\mathcal{B}_{p,s,\mathcal{M}}$, on which the essential spectral radius of \mathcal{L} , respectively \mathcal{M} , is $\leq \rho_1^{(p,s)}$. Set

$$\rho_{\infty}^{(p,s)}(T) = \lim_{n \rightarrow \infty} \left(\sup_{\mathcal{X}} \max((\lambda_w(T^n))^p, (\nu_w(T^n))^s) \right)^{1/n} < 1.$$

Clearly $\rho_{\infty}^{(p,s)}(T) \geq \rho_1^{(p,s)}(T)$ and, e.g., $\rho_{\infty}^{(-r/2,r/2)}(T) \leq \gamma^{-r/2}$.

We shall assume that T is C^{∞} and the stable foliation of T (or its unstable foliation) is C^{∞} . (This is a very strong assumption, and the corresponding case should be viewed as a “toy model” in which the features of our symbolic calculus approach are completely transparent: The heart of the proof is contained in a half page, between (2.8) and (2.9) below.) We introduce in Subsection 2.3, for p, s in \mathbb{R} and $1 < t < \infty$, a Banach space $W^{p,s-p,t}(\mathcal{X}) = W^{p,s-p,t}(\mathcal{X}, T)$ of distributions, based on $L^t(\text{Leb})$.¹

Our main result (Theorem 2.9) when the stable foliation is C^{∞} is that, if T is volume preserving, the essential spectral radius ρ_{ess} of \mathcal{L} on $W^{p,s-p,t}(\mathcal{X})$ is at most $\rho_{\infty}^{(p,s)}(T)$ for all $p < 0$, $s > 0$ and $t \in (1, \infty)$;

¹Controlling the spectrum on a scale of Sobolev spaces may be useful: see [5].

while if T does not preserve volume then $\limsup_{t \rightarrow \infty} \rho_{ess}(\mathcal{L}|_{W^{p,s-p,t}(\mathcal{X})}) \leq \rho_\infty^{(p,s)}(T)$. If the unstable foliation is C^∞ , the essential spectral radius of \mathcal{M} on $W^{p,s-p,t}(\mathcal{X}, T^{-1})$ is at most $\lim_{n \rightarrow \infty} \sup_{\mathcal{X}} |\det DT^n|^{-(t-1)/tn} \cdot \rho_\infty^{(-s,-p)}(T)$ for all $p < 0$, $s > 0$ and $t \in (1, \infty)$ (Theorem 2.12).

Propositions 2.11 and 2.13 give upper bounds related to $\rho_1^{(p,s)}(T)$: They imply

$$\begin{aligned} \limsup_{t \rightarrow \infty} \rho_{ess}(\mathcal{L}|_{W^{p,s-p,t}}) &\leq \lim_{n \rightarrow \infty} \|\det DT^n|_{E^u}\|_{L^\infty(\text{Leb})}^{1/n} \rho_1^{(p,s)}(T), \\ \limsup_{t \rightarrow 1} \rho_{ess}(\mathcal{L}|_{W^{p,s-p,t}}) &\leq \lim_{n \rightarrow \infty} \|(\det DT^n|_{E^s})^{-1}\|_{L^\infty(\text{Leb})}^{1/n} \rho_1^{(p,s)}(T). \end{aligned}$$

Finally, we study in the appendix the essential spectral radii of

$$\mathcal{L}_t \varphi = |\det DT|^{1/t} \cdot (\varphi \circ T), \quad \mathcal{M}_t \varphi = \frac{\varphi \circ T^{-1}}{|\det DT|^{1-1/t} \circ T^{-1}}.$$

The case when T is C^{r+1} (for some $r > 0$) and neither of the dynamical foliations is C^∞ , but at least one of them is $C^{1+\epsilon}$ (for $\epsilon > 0$) will be treated in a forthcoming work [4], using spaces due to Alinhac [1]. We hope that the (general) C^α foliation case will be amenable to the present approach. Gouëzel and Liverani [10] have independently obtained non trivial, but weaker, bounds for the essential spectral radius of \mathcal{M} , on a different Banach space, in this general case.

We end this introduction with three open problems:

Remark 1.1 (Links with SRB measures). With the techniques of Blank–Keller–Liverani [6], one should obtain that the spectral radius of \mathcal{L} on each $W^{p,q,t}(\mathcal{X})$ is one, that 1 is a semi-simple eigenvalue, and that the corresponding eigenvector (in the dual of $W^{p,q,t}(\mathcal{X})$) for the dual of \mathcal{L} is an invariant probability measure μ with ergodic basin of full Lebesgue measure. Furthermore, the multiplicity of the eigenvalue 1 is equal to the number of ergodic components of μ , and each ergodic component is an SRB measure. Also, if 1 is a simple eigenvalue then it is the only eigenvalue on the unit circle: this corresponds to exponential decay of correlations for smooth observables. If the unstable foliation is C^∞ , the SRB measure(s) of T can alternatively be constructed with the fixed point of \mathcal{M} in $W^{p,q,t}(\mathcal{X}, T^{-1})$. ²

²The operators \mathcal{L}_t , \mathcal{M}_t “interpolate” between the SRB measures of T , T^{-1} .

Remark 1.2 (Spectral stability). The perturbation techniques of [6], should imply stability of the spectrum of \mathcal{L} (including eigenprojectors) outside a disc of radius ρ , under stochastic and C^{r+1} deterministic perturbations of T , perhaps up to taking $\rho > \rho_\infty^{(p,s)}$. For deterministic perturbations \tilde{T} of T , the Banach spaces $W^{p,q,t}(\mathcal{X}, T)$ and $\widetilde{W}^{p,q,t} = W^{p,q,t}(\mathcal{X}, \tilde{T})$ are different. “Stability of the eigenprojector” Π of T associated to an eigenvalue τ of large enough modulus means the following (assume τ is simple): Let $\tilde{\mathcal{L}}$ denote the transfer operator of \tilde{T} ; then, if \tilde{T} is close enough to T , there are a Banach space W_ϵ contained in the intersection of $\widetilde{W}^{p,q,t}$ and $W^{p,q,t}$, a rank-one projector Π_ϵ (on W_ϵ , $\widetilde{W}^{p,q,t}$, and $W^{p,q,t}$), and a simple eigenvalue $(\tilde{\tau}, \tilde{\Pi})$ for $\tilde{\mathcal{L}}$ on $\widetilde{W}^{p,q,t}$, so that both $\|\Pi_\epsilon - \Pi\|_W$ and $\|\Pi_\epsilon - \tilde{\Pi}\|_{\widetilde{W}}$ are small.

Remark 1.3 (Essential decorrelation radius). For C^{r+1} expanding circle endomorphisms F , the essential spectral radius $\rho_{ess}(\mathcal{M}_F|_{C^r})$ of $\mathcal{M}_F\varphi(x) = \sum_{F(y)=x} \varphi(y)/|\det DF(y)|$ acting on C^r functions (see [9] and references therein) is equal to

$$\lim_{n \rightarrow \infty} \left(\int |(F^n)'(x)|^{-r} dLeb(x) \right)^{1/n} = \lim_{n \rightarrow \infty} \left(\int |(F^n)'(x)|^{-r} d\mu_{SRB}(x) \right)^{1/n}.$$

However, for C^{r+1} expanding maps in arbitrary dimension [11]

$$(1.2) \quad \begin{aligned} \rho_{ess}(\mathcal{M}_F|_{C^r}) &= \exp\left(\sup_\mu\{h_\mu - \int \log |\det DF| d\mu - r \cdot \chi_\mu\}\right) \\ &\leq \lim_{n \rightarrow \infty} \left(\int \sup_{|v|=1} |D_x(F^n)(v)|^{-r} dLeb(x) \right)^{1/n}, \end{aligned}$$

where μ ranges over ergodic F -invariant probability measures, h_μ is the entropy of μ , and χ_μ denotes the smallest (positive) Lyapunov exponent of DF . The inequality in (1.2) can be strict. In the other direction, note that $\rho_{ess}(\mathcal{M}_F|_{C^r}) \geq \exp(-r\chi_{\mu_{SRB}})$, and the inequality can be strict [9], even in dimension one. The results of Avila et al. [3], indicate that in dimension at least two there may be Banach spaces containing all C^r functions on which the essential spectral radius of \mathcal{M}_F is strictly smaller than $\rho_{ess}(\mathcal{M}_F|_{C^r})$. (This would imply [9] that $\rho_{ess}(\mathcal{M}_F|_{C^r})$ may be strictly larger than the essential decorrelation radius of F for C^r observables and thus $\rho_{point-ess}(\mathcal{M}_F|_{C^r}) < \rho_{ess}(\mathcal{M}_F|_{C^r})$.)

Let T be a transitive C^∞ Anosov diffeomorphism with both foliations C^∞ . Let $\rho_{ess}^+(p, s, t)$ and $\rho_{ess}^-(p, s, t)$ be the essential spectral radii of \mathcal{L}

acting on $W^{p,s-p,t}(\mathcal{X})$ and $W^{-p,-s+p,t}(\mathcal{X}, T^{-1})$, respectively, and set

$$\rho(r) := \min\left(\inf_{\substack{t,p \in (-r,0) \\ s \in (0,r+p)}} \rho_{ess}^+(p,s,t), \inf_{\substack{t,p \in (-r,0) \\ s \in (0,r+p)}} \rho_{ess}^-(p,s,t)\right).$$

We expect that $\inf_{\mathcal{B}_r} \rho_{ess}(\mathcal{L}|_{\mathcal{B}_r})$, where \mathcal{B}_r spans all Banach spaces of distributions of order $\leq r$, containing all C^r functions, and on which \mathcal{L} acts boundedly, coincides with the essential decorrelation radius $\hat{\rho}(r)$ of T for C^r functions, and that $\hat{\rho}(r) < \rho(r)$ can occur.

2. BOUNDING THE ESSENTIAL SPECTRAL RADIUS

2.1. Preliminaries. From now on and until the end of Subsection 2.6, T is Anosov and C^∞ , with a C^∞ stable foliation \mathcal{F}^s . Write $I = (-1, 1)$, and let d_s be the dimension of \mathcal{F}^s . We work with C^∞ foliated charts κ, V : let $\cup_{i \in \mathcal{I}} V_i$ be a finite covering of \mathcal{X} by small open sets, and let $U_i = I^d = I^{d_s} \times I^{d-d_s}$ be $\#\mathcal{I}$ disjoint copies of I^d , viewed as subsets of disjoint copies \mathbb{R}_i^d of \mathbb{R}^d . Let $\kappa_i : V_i \rightarrow U_i$ be C^∞ diffeomorphisms so that κ_i^{-1} of each horizontal segment is the intersection of a leaf of \mathcal{F}^s with V_i . In addition, we require that $\kappa_i^{-1}(\{(0, y)\})$ is the unstable leaf of $\kappa_i^{-1}(0, 0)$ intersected with V_i (this is a way to require closeness of the vertical foliation in I^d and the image of leaves of the unstable foliation \mathcal{F}^u).

Choose a C^∞ partition of the unity $\{\psi_i\}$ on \mathcal{X} , compatible with $V = \{V_i\}$, i.e., each ψ_i is supported in V_i . Then, for each $n \geq 1$

$$(2.1) \quad \mathcal{L}^n \varphi(w) = \sum_{i,j} \psi_j(T^n(w)) \psi_i(w) \cdot \varphi(T^n(w)).$$

If $V_{ij} = V_{ij,n} := T^{-n}(V_j) \cap V_i \neq \emptyset$, setting $U_{ij,n} := \kappa_i(T^{-n}(V_j) \cap V_i) \subset U_i$, the map $T_{ij}^n : U_{ij,n} \rightarrow U_j$ has a derivative in block form:

$$\begin{pmatrix} A_{ij,n}^{tr}(x, y) & B_{ij,n}^{tr}(x, y) \\ 0 & D_{ij,n}^{tr}(x, y) \end{pmatrix}, \quad (x, y) \in (I^{d_s}, I^{d-d_s}),$$

with $A_{ij,n}$ a $d_s \times d_s$ matrix, $D_{ij,n}$ a $(d - d_s) \times (d - d_s)$ matrix, and

$$(2.2) \quad \begin{aligned} |A_{ij,n}(x, y)| &\leq \nu_{ij}(T^n) := \sup_{w \in V_{ij}} \nu_w(T^n) < 1, \\ |D_{ij,n}(x, y)^{-1}| &\leq \lambda_{ij}(T^n)^{-1} := \sup_{w \in V_{ij}} (\lambda_{T^n(w)}(T^n))^{-1} < 1. \end{aligned}$$

Furthermore, for each ϵ , there exists δ so that if $\text{diam } V < \delta$ then

$$(2.3) \quad |B_{ij,n}(x, y)v| \leq \epsilon |D_{ij,n}(x, y)v|, \quad \forall n \geq 1, \forall v \in \mathbb{R}^{d-d_s}.$$

2.2. Elementary spaces $W^{p,q,t}(\mathbb{R}^d)$. Let p and q be real numbers. We introduce the “symbol” $a_{p,q}(\xi, \eta)$, for $(\xi, \eta) \in \mathbb{R}^{d_s} \times \mathbb{R}^{d-d_s}$:

$$a_{p,q}(\xi, \eta) = (1 + |\xi|^2 + |\eta|^2)^{p/2}(1 + |\xi|^2)^{q/2}.$$

The corresponding linear operator $a_{p,q}^{Op}$ maps the space \mathcal{S} of rapidly decaying C^∞ functions on \mathbb{R}^d into itself via

$$a_{p,q}^{Op}(f)(x, y) = (2\pi)^{-d} \int \int e^{ix\xi} e^{iy\eta} a_{p,q}(\xi, \eta) \hat{f}(\xi, \eta) d\xi d\eta,$$

where the Fourier transform of f is $\hat{f}(\xi, \eta) = \int \int e^{-ix\xi} e^{-iy\eta} f(x, y) dx dy$.

Definition 2.1 (Anisotropic Sobolev spaces). For $1 \leq t \leq \infty$, let $W^{p,q,t}(\mathbb{R}^d)$ be the closure of $\{f \in \mathcal{S}(\mathbb{R}^d)\}$ for the $L^t(\mathbb{R}^d, \text{Leb})$ norm of $a_{p,q}^{Op}(f)$, with induced norm, denoted $\|\cdot\|_{p,q,t,\mathbb{R}^d}$.

By construction, $a_{p,q}^{Op}$ extends to a bounded invertible operator from $W^{p,q,t}(\mathbb{R}^d)$ to $L^t(\mathbb{R}^d)$. Clearly, $H^{p,q}(\mathbb{R}^d) = W^{p,q,2}(\mathbb{R}^d)$ is a Hilbert space.

Lemma 2.2 (Boundedness/compactness of embedding). *Assume that $1 < t < \infty$. Denote by $W_C^{p',q',t}(\mathbb{R}^d)$ those $f \in W^{p',q',t}(\mathbb{R}^d)$ supported in a compact subset of \mathbb{R}^d . If $q' \geq q$ and $p' \geq p$ then the natural injection $W_C^{p',q',t}(\mathbb{R}^d) \subset W^{p,q,t}(\mathbb{R}^d)$ is bounded. This injection is compact if $q' \geq q$ and $p' > p$.*

Proof. If $t = 2$, the proofs of Theorems 2.5.2 and 2.5.3 in [13] adapt readily. The general case is an easy exercise. \square

Remark 2.3. More generally, we may introduce classes of (symbols) of pseudodifferential operators: Let p and q be real numbers. We say that $b \in C^\infty(I^d \times \mathbb{R}^d, \mathbb{R})$, belongs to $S^{p,q}$ if for any multi-indices³ $\alpha = (\alpha', \alpha'')$ and $\beta = (\beta', \beta'')$ in $\mathbb{Z}_+^{d_s+(d-d_s)}$, there exists $C_{\alpha,\beta}$ so that

$$\sup \left| \partial_\xi^{\alpha'} \partial_\eta^{\alpha''} \partial_x^{\beta'} \partial_y^{\beta''} b(x, y, \xi, \eta) \right| \leq C_{\alpha,\beta} (1 + |\xi| + |\eta|)^{p - |\alpha''|} (1 + |\xi|)^{q - |\alpha'|}.$$

The spaces $S^{p,q}$ and $H^{p,q}$ were studied by Kordyukov [15]. The 1963 edition of Hörmander’s book [13, II.2.5] contains a treatment of a special case of the spaces $S^{p,q}$ when $d_s = 1$. See also Sablé-Tougeron [17] for applications of these special cases.

³We decompose multi-indices $\gamma = (\gamma', \gamma'')$ in this way tacitly from now on.

2.3. Banach spaces $W^{p,q,t}(\mathcal{X})$ and Leibniz formula. Let κ, V be a chart and ψ be a compatible partition of unity as in Subsection 2.1.

Definition 2.4. Let p, q be real numbers, and let $1 \leq t \leq \infty$. $W^{p,q,t}(\mathcal{X}, \kappa, V, \psi)$ is $\{\varphi \in \mathcal{D}'(\mathcal{X}) \mid (\psi_i \cdot \varphi) \circ \kappa_i^{-1} \in W^{p,q,t}(\mathbb{R}_i^d), \forall i \in \mathcal{I}\}$, normed by

$$\|\varphi\|_{p,q,t} = \sum_{i \in \mathcal{I}} \|(\psi_i \cdot \varphi) \circ \kappa_i^{-1}\|_{p,q,t,\mathbb{R}_i^d}.$$

Remark 2.5. If $1 < t < \infty$, the Banach spaces $W^{p,q,t}(\mathcal{X}, \kappa, V, \psi)$ are independent of the charts (κ, V) and of the partition of unity ψ : A version of the change of variables theorem for pseudodifferential operators, see e.g. [2, I.7.1], shows that the norms corresponding to different (κ, V, ψ) are equivalent. (See Lemmas 2.8 and 2.10 below.) We may thus write $W^{p,q,t}(\mathcal{X})$. $H^{p,q}(\mathcal{X}) = W^{p,q,2}(\mathcal{X})$ is a Hilbert space.

Remark 2.6. $W^{p,q,t}(\mathcal{X})$ is the Banach space of distributions f on \mathcal{X} so that $(1 + \Delta_s)^{q/2}(1 + \Delta)^{p/2}f \in L^t(\mathcal{X})$, with the induced $L^t(\mathcal{X})$ norm, where Δ is the Laplacian and Δ_s is the stable foliated Laplacian. In particular, if $p \leq 0$ and $0 \leq q \leq r$, it contains all C^r functions.

We start with a useful remark:

Lemma 2.7 (Proper support). *For every compact subsets K_1, K_2 of I^d , with K_1 included in the interior of K_2 , and for every $1 < t < \infty$, p, q , there are $C > 0$ and a C^∞ function $\Psi_K : \mathbb{R}^d \rightarrow [0, 1]$, supported in K_2 , so that for each $f \in W^{p,q,t}(\mathbb{R}^d)$ supported in K_1 ,*

$$\|\Psi_K \cdot a_{p,q}^{Op}(f) - a_{p,q}^{Op}(f)\|_{L^t} \leq C\|f\|_{p-1,q,t}.$$

Proof. Using that the kernel of a pseudo-differential operator is C^∞ outside of the diagonal, a standard construction allows to write $\Psi \cdot a - a$ (acting on compactly supported distributions) as an operator with a C^∞ kernel (see e.g. [2, Prop 6.3]). Integrate by parts to conclude. \square

Lemma 2.8 (Leibniz formula). *Let $1 < t < \infty$, let p, q be real numbers and let h be a compactly supported C^∞ function on I^d . Then there is $C(h) > 0$, and there exists $C_x(h)$, depending only on*

$$(2.4) \quad \sup_{|\beta'| \in \{1,2\}, (x,y) \in I^d} |\partial_x^{\beta'} h(x, y)|,$$

so that for every $f \in W^{p,q,t}(\mathbb{R}^d)$

$$(2.5) \quad a_{p,q}^{Op}(h \cdot f) = h \cdot a_{p,q}^{Op}(f) + g_1 + g_2,$$

with $\|g_1\|_{L^t} \leq C_x(h)\|f\|_{p,q-1,t}$ and $\|g_2\|_{L^t} \leq C(h)\|f\|_{p-1,q,t}$.

Proof. Multiplication by h is a pseudodifferential operator. Composing it with $a_{p,q}^{Op}$, we get a new operator b^{Op} . Using a Taylor series of order one (see e.g. [2, Théorème I.4.1 and §I.8.2]), we find $b(x, y, \xi, \eta) =$

$$\begin{aligned} & a_{p,q}(\xi, \eta) \cdot h(x, y) + \frac{2}{(2\pi)^d} \sum_{|\alpha|+|\beta|=2} \frac{(-1)^{|\alpha|+|\beta|}}{\alpha!\beta!} \int_0^1 (1-s) \cdot \\ & \cdot \int e^{-i(u,v)(\omega,\theta)} \omega^{\beta'} \theta^{\beta''} u^{\alpha'} v^{\alpha''} \cdot \partial_\omega^{\beta'} \partial_\theta^{\beta''} a_{p,q}(\xi - s\omega, \eta - s\theta) d\omega d\theta \\ & \cdot \partial_u^{\alpha'} \partial_v^{\alpha''} h(x - su, y - sv) du dv ds . \end{aligned}$$

The symbol $a_{p,q}(\xi, \eta) \cdot h(x, y)$ gives rise to the first term in the right-hand-side of (2.5). For the remainder term, the usual integrations by parts [2, §I.8.2, p.56] yield a linear combination of terms

$$\begin{aligned} b^{\gamma,j}(x, y, \xi, \eta) := & \int_0^1 (1-s)s^j \cdot \int e^{-i(u,v)(\omega,\theta)} \cdot \partial_\omega^{\gamma'} \partial_\theta^{\gamma''} a_{p,q}(\xi - s\omega, \eta - s\theta) \\ & \cdot \partial_u^{\gamma'} \partial_v^{\gamma''} h(x - su, y - sv) d\omega d\theta du dv ds , \end{aligned}$$

where $j \in \{0, 1, 2\}$ and $|\gamma'|+|\gamma''| \in \{1, 2\}$ (the number of terms and the coefficients in the linear combination are independent of h and $a_{p,q}$). If $|\gamma''| = 0$ then $|\gamma'| \in \{1, 2\}$, and this gives g_1 , as we explain next. Define a symbol $\tilde{b} = b^{\gamma,j}(a_{p,q-1})^{-1}$. By [8, Théorème 9] it suffices to show that there is $C_x(h)$ so that $\sup |\partial_{x,y}^\alpha \partial_{\xi,\eta}^\beta \tilde{b}(x, y, \xi, \eta)| \leq C_x(h)(1 + |\xi| + |\eta|)^{-|\beta|}$, for all $|\alpha| \leq 1$ and all β . This can be shown by a straightforward (although tedious) implementation of the standard oscillatory integral argument [2, §I.8.2, p.56]. Finally, if $|\gamma''| \geq 1$ then the term corresponding to $b^{\gamma,j}$ may be included in g_2 , working with $b^{\gamma,j}(a_{p-1,q})^{-1}$. \square

2.4. Bounding the essential spectral radius of \mathcal{L} .

Theorem 2.9. *Let T be a C^∞ Anosov diffeomorphism on a compact manifold, with a C^∞ stable foliation. For any $p < 0$, $s > 0$, and $t \in (1, \infty)$, the essential spectral radius of \mathcal{L} on $W^{p,s-p,t}(\mathcal{X})$ is not larger than $\lim_{n \rightarrow \infty} \sup_{\mathcal{X}} |\det DT^n|^{-1/tn} \cdot \rho_\infty^{(p,s)}(T)$.*

Note that the essential spectral radius of the dual of \mathcal{L} i.e. (an extension of) \mathcal{M} acting on the dual of $W^{p,s-p,t}(\mathcal{X})$ coincides with the essential spectral radius of \mathcal{L} on $W^{p,s-p,t}(\mathcal{X})$. Also, if the unstable foliation is C^∞ , then $\varphi \mapsto \varphi \circ T^{-1}$ on $W^{p,s-p,t}(\mathcal{X}, T^{-1})$ has essential spectral radius $\leq \lim_{n \rightarrow \infty} \sup_{\mathcal{X}} |\det DT^{-n}|^{-1/tn} \cdot \rho_\infty^{(p,s)}(T^{-1})$ (note that $\rho_\infty^{(p,s)}(T^{-1}) = \rho_\infty^{(-s,-p)}(T)$).

It is convenient to extend each $T_{ij}^n = \kappa_j \circ T^n \circ \kappa_i^{-1} : U_{ij,n} \rightarrow U_j$ to a C^∞ diffeomorphism from \mathbb{R}_i^d onto its image in \mathbb{R}_j^d in such a way that the

intersection of U_j with the image of U_i by the extended map coincides with $T_{ij}^n(U_j)$, and so that the extended map is the identity outside of a large compact set. (The extension is still noted T_{ij}^n .) The theorem will be a consequence of the following lemma, proved in §2.6:

Lemma 2.10 (Lasota-Yorke inequality). *There exist $\delta_0 > 0$ and C_0 , so that for each cover with $\text{diam } V < \delta_0$, and for each $n \geq 1$ there exists $C(n) > 1$, so that for every $f \in W^{p,q,t}(\mathbb{R}_j^d)$, compactly supported in U_j , and each C^∞ function $\Psi_{ij} : \mathbb{R}_i^d \rightarrow [0, 1]$ compactly supported in $U_{ij,n}$*

$$\begin{aligned} & \|\Psi_{ij} \cdot a_{p,q}^{Op}(f \circ T_{ij}^n)\|_{L^t} \cdot \inf_{V_{ij}} |\det DT^n|^{1/t} \\ & \leq C_0 \cdot \max((\lambda_{ij}(T^n))^p, (\nu_{ij}(T^n))^{q+p}) \|f\|_{p,q,t,\mathbb{R}_j^d} \\ & \quad + C(n) \|f\|_{p-1/2,q,t,\mathbb{R}_j^d}, \quad \forall p \leq 0, q \geq -p, 1 < t < \infty. \end{aligned}$$

Proof of Theorem 2.9 using Lemma 2.10. Let δ_0 be as in Lemma 2.10. For $\delta < \delta_0$, let (κ, V) be a foliated chart of diameter at most δ , and let ψ be an adapted partition of unity. Set $f_j|_{U_j} = (\psi_j \cdot \varphi) \circ \kappa_j^{-1}$, extending by zero on \mathbb{R}_j^d . By definition, for all $n \geq 1$,

$$\|\mathcal{L}^n \varphi\|_{p,q,t} \leq \sum_i \sum_{j: T^n(V_i) \cap V_j \neq \emptyset} \|(\psi_i \circ \kappa_i^{-1}) \cdot (f_j \circ T_{ij}^n)\|_{p,q,t,\mathbb{R}_i^d}.$$

By Lemma 2.7, there is a C^∞ function $\Psi_{ij} : \mathbb{R}_i^d \rightarrow [0, 1]$, supported in a compact subset of $U_{ij,n}$, so that $\|(\psi_i \circ \kappa_i^{-1}) \cdot (f_j \circ T_{ij}^n)\|_{p,q,t,\mathbb{R}_i^d} \leq$

$$\|\Psi_{ij} a_{p,q}^{Op}((\psi_i \circ \kappa_i^{-1}) f_j \circ T_{ij}^n)\|_{L^t} + C \|(\psi_i \circ \kappa_i^{-1})(f_j \circ T_{ij}^n)\|_{p-1,q,t}.$$

By Lemma 2.8, the first term in the above sum is bounded by

$$C(\psi) \cdot \|\Psi_{ij} a_{p,q}^{Op}(f_j \circ T_{ij}^n)\|_{L^t} + C(\psi) \cdot \|(f_j \circ T_{ij}^n)\|_{p-1,q,t}.$$

Set $\rho(p, s, n) = \max_{i,j} \max((\lambda_{ij}(T^n))^p, (\nu_{ij}(T^n))^s)$. By Lemma 2.10

$$\begin{aligned} & \|\mathcal{L}^n \varphi\|_{p,s-p,t} \cdot \inf_{V_{ij}} |\det DT^n|^{1/t} \\ & \leq C_0 C(\psi) \rho(p, s, n) \cdot \sum_{i,j} \|a_{p,s-p}^{Op}((\psi_j \cdot \varphi) \circ \kappa_j^{-1})\|_{L^t} \\ & \quad + C(n, \psi) \sum_{i,j} \|(\psi_j \cdot \varphi) \circ \kappa_j^{-1}\|_{p-1/2,s-p,t} \\ & \leq \#\mathcal{I} \cdot C_0 C(\psi) \rho(p, s, n) \cdot \sum_j \|(\psi_j \cdot \varphi) \circ \kappa_j^{-1}\|_{p,s-p,t} \\ & \quad + \#\mathcal{I} \cdot C(n, \psi) \sum_j \|(\psi_j \cdot \varphi) \circ \kappa_j^{-1}\|_{p-1/2,s-p,t} \\ & \leq C_1 \rho(p, s, n) \cdot \|\varphi\|_{p,s-p,t} + C_2(n) \|\varphi\|_{p-1/2,s-p,t}. \end{aligned}$$

By Lemma 2.2, we can apply Hennion's theorem [12]. \square

2.5. Bounds involving averaged hyperbolicity exponents.

Proposition 2.11. *Let T be a C^∞ Anosov diffeomorphism on a compact manifold, with a C^∞ stable foliation. For any $p < 0$, $s > 0$, and $1 < t < \infty$, the essential spectral radius of \mathcal{L} on $W^{p,s-p,t}(\mathcal{X})$ is*

$$\begin{aligned} &\leq \lim_{n \rightarrow \infty} \left(\int_{\mathcal{X}} \max((\lambda_w(T^n))^p, (\nu_w(T^n))^s) \right. \\ &\quad \cdot |\det DT^n|_{E^u}| \cdot |\det DT^n|^{-1/t} dLeb(w) \left. \right)^{1/n} \\ &= \lim_{n \rightarrow \infty} \left(\int_{\mathcal{X}} \max((\lambda_w(T^n))^p, (\nu_w(T^n))^s) \right. \\ &\quad \cdot |\det DT^n|_{E^s}|^{-1} \cdot |\det DT^n|^{1-1/t} dLeb(w) \left. \right)^{1/n}. \end{aligned}$$

Proof. The reader is invited to check that there is $C_3 > 1$ (depending on T) so that for all $n \geq 1$, each cover V , all i, j , all $p \leq 0$

$$\max_{w \in \overline{V}_{ij,n}} (\lambda_w(T^n))^p - \min_{w \in \overline{V}_{ij,n}} (\lambda_w(T^n))^p \leq nC_3(\lambda_{ij}(T^n))^p \text{diam } V,$$

and similarly for the ν_w (this is a bounded distortion argument). If $\ell_{ij}(n) := \max((\lambda_{ij}(T^n))^p, (\nu_{ij}(T^n))^s) = (\lambda_{ij}(T^n))^p$ (the other case is similar) then

$$\begin{aligned} \max_{w \in \overline{V}_{ij}} (\ell_{ij}(n) - \max((\lambda_w(T^n))^p, (\nu_w(T^n))^s)) &\leq \ell_{ij}(n) - \min_{w \in \overline{V}_{ij}} (\lambda_w(T^n))^p \\ &\leq \max_{w \in \overline{V}_{ij}} (\lambda_w(T^n))^p - \min_{w \in \overline{V}_{ij}} (\lambda_w(T^n))^p. \end{aligned}$$

Choose a partition $\mathcal{X} = \cup_{i \in \mathcal{I}} W_i$ with $W_i \subset V_i$, and write $W_{ij} = W_i \cap T^{-n}W_j$. Then

$$\begin{aligned} &\sum_{i,j} \text{Leb}(W_{ij}) \ell_{ij}(n) - \int_{\mathcal{X}} \max((\lambda_w(T^n))^p, (\nu_w(T^n))^s) dLeb \\ &\leq \sum_{i,j} \text{Leb}(W_{ij}) \left(\ell_{ij}(n) - \min_{W_{ij}} \max((\lambda_w(T^n))^p, (\nu_w(T^n))^s) \right) \\ &\leq C_3 n \cdot \text{diam } V \sum_{i,j} \text{Leb}(W_{ij}) \ell_{ij}(n). \end{aligned}$$

Therefore, fixing $\delta \in (0, 1)$, if $V(n)$ satisfies $\text{diam } V(n) = \delta/(C_3 n)$,

$$\sum_{i,j} \text{Leb}(V_{ij,n}) \ell_{ij}(n) \leq \frac{\#V(n)}{(1-\delta)} \int_{\mathcal{X}} \max((\lambda_w(T^n))^p, (\nu_w(T^n))^s) dLeb.$$

Choose $V(n)$ and $\psi(n)$ with $\#V = O(n)$ and $(\min_i \text{Leb}(V_i))^{-1} = O(n^d)$, ensuring that the derivatives of the ψ_i from Lemma 2.8 satisfy $O(n^Q)$ bounds; for some $Q \geq 1$. Finally, there is $C_4 \geq 1$ so that

$$\frac{1}{\text{Leb}(V_{ij,n})} \leq \frac{C_4}{\min_i \text{Leb}(V_i)} \inf_{V_{ij,n}} |\det DT^n|_{E^u}|.$$

for all n and all covers V . Lemma 2.10 allows to conclude, by a straightforward adaptation of the proof of Theorem 2.9. \square

2.6. Proof of the Lasota-Yorke inequality.

Proof of Lemma 2.10. We replace T by T^n (the reader should keep in mind that A_{ij} , B_{ij} , D_{ij} , λ_{ij} , and ν_{ij} depend on n) and drop the indices i , j . We study the action of the composition by T on our symbol $a_{p,q}(\xi, \eta)$ (see e.g. [2, Chapter I.7, Proposition 7.1, and Chapter I.8, Théorème 3]).

Taking a Taylor series of order 0 (i.e., $k = 1$ in the proof of [2, I.8, Lemme 4]), we find that $(\Psi_{ij}a_{p,q}(\xi, \eta)^{Op}(f \circ T)) \circ T^{-1}$ decomposes as

$$(2.6) \quad (\Psi_{ij} \circ T^{-1}) \cdot ((a_{p,q}((DT)^{tr}_{T^{-1}(x,y)}(\xi, \eta))^{Op}(f) + r_1(x, y, \xi, \eta)^{Op}(f) + r_2(x, y, \xi, \eta)^{Op}(f)),$$

where r_1 and r_2 are described next. The symbol $r_1(T(x, y), \xi, \eta)$ is a universal finite linear combination of

$$(2.7) \quad \begin{aligned} & \int_{\mathbb{R}^d} dudv \int_{\mathbb{R}^d} d\omega d\theta e^{-i(u,v)(\omega,\theta)} \int_0^1 ds (1-s)s^j \\ & \cdot \partial_{u_\ell} (e^{i(R_{(x,y)}(x+su,y+sv))^{tr}(\xi,\eta)}) \\ & \cdot (1 + |s\omega + A_{(x,y)}\xi|^2 + |s\theta + B_{(x,y)}\xi + D_{(x,y)}\eta|^2)^{p/2} \\ & \cdot \partial_{\omega_\ell} (1 + |s\omega + A_{(x,y)}\xi|^2)^{q/2} \chi \left(\frac{(s\omega + A_{(x,y)}\xi, s\theta + B_{(x,y)}\xi + D_{(x,y)}\eta)}{1 + |(A_{(0,0)}\xi, B_{(0,0)}\xi + D_{(0,0)}\eta)|} \right), \end{aligned}$$

where $j \in \{0, 1\}$, $1 \leq \ell \leq d_s$, the function $\chi : \mathbb{R}^d \rightarrow [0, 1]$ is C^∞ and compactly supported in a suitable annulus, and

$$R_{(x,y)}(u, v) = T(u, v) - T(x, y) - DT_{(x,y)}(u - x, v - y).$$

To describe r_2 , set $\tilde{r}_2 = r_2 \cdot (a_{p-1/2,q})^{-1}$, so that $r_2^{Op} = \tilde{r}_2^{Op} a_{p-1/2,q}^{Op}$. (In the proof we shall use the notation $\tilde{r} = r \cdot (a_{p-1/2,q})^{-1}$ several times.)

We claim that \tilde{r}_2^{Op} is a bounded operator on $L^t(\mathbb{R}^d, \text{Leb})$, so that

$$\begin{aligned} \|\Psi_{ij} \cdot ((\tilde{r}_2^{Op} f) \circ T)\|_{L^t} &\leq C \sup_{V_{ijj}} |\det DT|^{-1/t} \cdot \left(\int |\tilde{r}_2^{Op}(f)|^t d\text{Leb} \right)^{1/t} \\ &\leq C_2(n) \|f\|_{p-1/2, q, t, \mathbb{R}_j^d}. \end{aligned}$$

By [8, Théorème 9] it suffices to show that for all $|\alpha| \leq 1$ and all β we have $\sup |(1 + |\xi| + |\eta|)^{|\beta|} \partial_{x,y}^\alpha \partial_{\xi,\eta}^\beta \tilde{r}_2(x, y, \xi, \eta)| < \infty$. This can be seen by observing that r_2 is made on the one hand with contributions due to $1 - \chi$, which have rapid decay in $1 + |(\omega, \theta)| + |(A_{(0,0)}\xi, B_{(0,0)}\xi + D_{(0,0)}\eta)|$ (by a small modification of [2, p.58], using bounded distortion for DT^n). The other terms forming r_2 correspond to a ∂_{θ_ℓ} derivative, or to a ∂_{ω_ℓ} , but acting on a factor $(1 + |s\omega + A_{(x,y)}\xi|^2 + |s\theta + B_{(x,y)}\xi + D_{(x,y)}\eta|^2)^{p/2}$. (Details are left to the reader, see [2, p.60].)

We may thus concentrate on the first two terms in (2.6). The first one is called the *principal symbol*.

We get $a_{p,q}((DT_{(x,y)})^{tr}(\xi, \eta))^{Op} = b^{Op} \circ a_{p,q}^{Op}$ by setting $b(x, y, \xi, \eta) = a_{p,q}((DT_{(x,y)})^{tr}(\xi, \eta)) / a_{p,q}(\xi, \eta)$. Again by [8, Théorème 9] it suffices to show that, up to replacing b by $b - r_3$, with \tilde{r}_3^{Op} bounded on each L^t , we have $\sup |(1 + |\xi| + |\eta|)^{|\beta|} \partial_{x,y}^\alpha \partial_{\xi,\eta}^\beta b| \leq (C_\delta/2) \max(\lambda^p, \nu^{q+p})$, for all $|\alpha| \leq 1$ and all β . Of course, we must also prove the same bounds for $r_1 \cdot (a_{p,q})^{-1}$ (modulo $r_4 + r_5$, with \tilde{r}_4^{Op} and \tilde{r}_5^{Op} bounded on each $L^t(\mathbb{R}^d)$).

Consider first $\alpha = \beta = 0$ and the principal symbol, i.e., the bound for $\sup |b|$. For $\xi \neq 0$ write $\nu_\xi = \sup_{x,y} |A_{(x,y)}\xi|/|\xi|$. Then, setting $\Lambda_1 = \max_\xi ((1 - 2\nu_\xi)/\nu_\xi)$, we get for any $|\xi| \geq \Lambda_1$

$$(2.8) \quad (1 + |A_{(x,y)}\xi|^2)^{q/2} \leq (1 + \nu_\xi^2 |\xi|^2)^{q/2} \leq 2\nu_\xi^q (1 + |\xi|^2)^{q/2}.$$

For $|\xi| < \Lambda_1$ we always have $(1 + |A_{(x,y)}\xi|^2)^{q/2} \leq (1 + |\xi|^2)^{q/2}$.

If $|\xi| \geq \max(\Lambda_1, |\eta|)$ then ⁴

$$(1 + |A_{(x,y)}\xi|^2 + |B_{(x,y)}\xi + D_{(x,y)}\eta|^2)^{p/2} \leq 2\nu_{\xi/|\xi|}^p (1 + |\xi|^2 + |\eta|^2)^{p/2}.$$

For $\eta \neq 0$ write $\lambda_\eta = \inf_{x,y} |D_{(x,y)}\eta|/|\eta|$. Fix $\Lambda_2 = \max_\eta \lambda_\eta$. If $\epsilon < 1/4$ and $|\eta| \geq \max(\Lambda_2, |\xi|)$ then ⁵

$$(1 + |A_{(x,y)}\xi|^2 + |B_{(x,y)}\xi + D_{(x,y)}\eta|^2)^{p/2} \leq 3\lambda^p (1 + |\xi|^2 + |\eta|^2)^{p/2}.$$

Finally, if $|\xi| \leq \Lambda_1$, and $|\eta| \leq \Lambda_2$, there is $C_{\Lambda_1, \Lambda_2}(n)$ with

$$(2.9) \quad (1 + |A_{(x,y)}\xi|^2 + |B_{(x,y)}\xi + D_{(x,y)}\eta|^2)^{p/2} \leq C_{\Lambda_1, \Lambda_2} (1 + |\xi|^2 + |\eta|^2)^{p/2-1}.$$

⁴Here we pay the price of $p < 0$.

⁵If $|\xi|$ is small but $|\eta|$ is large we need $p < 0$ to get a contraction here.

We include the above contribution in r_3 .

To bound $\sup_{x,y,\xi,\eta} |r_1 \cdot (a_{p,q})^{-1}|$, multiply the integrand of (2.7) by

$$\left(1 - \tilde{\chi}\left(\frac{s\omega + A_{(x,y)}\xi}{1 + |A_{(0,0)}\xi|}\right)\right) + \tilde{\chi}\left(\frac{s\omega + A_{(x,y)}\xi}{1 + |A_{(0,0)}\xi|}\right),$$

where $\tilde{\chi} : \mathbb{R}^{d_s} \rightarrow [0, 1]$ is C^∞ and compactly supported in an annulus. We consider separately the two terms in this decomposition:

The term containing $\chi \cdot (1 - \tilde{\chi})$ enjoys $C_k(n)(1 + |A_{(0,0)}\xi| + |\omega|)^{-k}$ rapid decay (adapting [2, p.58]). By choosing first k and then Λ_3 we get a bound $(C_\delta/4) \max(\lambda^p, \nu^{q+p})$ for $|\xi| \geq \Lambda_3$. If $|\xi| \leq \Lambda_3$, we use that if $|\eta| > \max(|\xi|, \Lambda_4)$ then

$$(2.10) \quad \begin{aligned} & \sup_{s,(\omega,\theta),(u,v),(x,y)} (1 + |s\omega + A_{(x,y)}\xi|^2 + |s\theta + B_{(x,y)}\xi + D_{(x,y)}\eta|^2)^{p/2} \\ & \cdot \chi\left(\frac{(s\omega + A_{(x,y)}\xi, s\theta + B_{(x,y)}\xi + D_{(x,y)}\eta)}{1 + |(A_{(0,0)}\xi, B_{(0,0)}\xi + D_{(0,0)}\eta)|}\right) \\ & \leq 2\lambda^p(1 + |\xi|^2 + |\eta|^2)^{p/2}. \end{aligned}$$

The compact set $\{|\xi| \leq \Lambda_3, |\eta| \leq \Lambda_4\}$ gives rise to a term r_4 .

For the $\chi \cdot \tilde{\chi}$ term, use the ideas exploited for the principal symbol (see also – again – [2, p.60]) to get a bound $(C_\delta/4) \max(\lambda^p, \nu^{q+p})$, up to a perturbation r_5 . In particular, if $|\xi|$ is large with respect to $|\eta|$ then

$$(2.11) \quad \begin{aligned} & \sup_{s,(\omega,\theta),(x,y)} (1 + |s\omega + A_{(x,y)}\xi|^2 + |s\theta + B_{(x,y)}\xi + D_{(x,y)}\eta|^2)^{p/2} \\ & \cdot \partial_{\omega_\ell} ((1 + |s\omega + A_{(x,y)}\xi|^2)^{q/2} \chi(\dots) \cdot \tilde{\chi}(\dots)) \end{aligned}$$

is bounded by $C(1 + |\xi| + |\eta|)^{p-1}(1 + |\xi|)^q$ (giving a contribution r_5); while if $|\eta|$ is large then (2.11) is bounded by $2\lambda^p(1 + |\xi|^2 + |\eta|^2)^{p/2}(1 + |\xi|^2)^{q/2}$.

The control of the derivatives of b and $r_1 \cdot (a_{p,q})^{-1}$, i.e., the case of nonzero $|\alpha| + |\beta|$, is straightforward although rather tedious. \square

2.7. The essential spectral radius of \mathcal{M} . Let T be a C^∞ Anosov diffeomorphism on a compact manifold, with a C^∞ unstable foliation. Let $W^{p,q,t}(\mathcal{X}, T^{-1})$ denote the Banach space in Definition 2.4. (We use now stable foliation of T^{-1} , i.e. the unstable foliation of T , in other words, $W^{p,q,t}(\mathcal{X}, T^{-1}) = (1 + \Delta_u)^{-q/2}(1 + \Delta)^{-p/2}(L^t(\mathcal{X}))$.)

Theorem 2.12 (Essential spectral radius of \mathcal{M}). *For any $p < 0$ and $s > 0$, the essential spectral radius of \mathcal{M} on $W^{p,s-p,t}(\mathcal{X}, T^{-1})$ is not larger than $\lim_{n \rightarrow \infty} \sup_{\mathcal{X}} |\det DT^n|^{-(t-1)/tn} \cdot \rho_\infty^{(-s,-p)}(T)$ for $t \in (1, \infty)$.*

Proposition 2.13. *For any $p < 0$, $s > 0$, and $1 < t < \infty$, the essential spectral radius of \mathcal{M} on $W^{p,s-p,t}(\mathcal{X}, T^{-1})$ is*

$$(2.12) \quad \begin{aligned} &\leq \lim_{n \rightarrow \infty} \left(\int_{\mathcal{X}} \max((\lambda_w(T^n))^{-s}, (\nu_w(T^n))^{-p}) \right. \\ &\quad \cdot |\det DT^n|_{E^u}| \cdot |\det DT^n|^{-(t-1)/t} dLeb(w) \left. \right)^{1/n}. \end{aligned}$$

Proof of the theorem and the proposition. Adapt the proofs of Theorem 2.9 and Proposition 2.11, using distortion estimates to bound (2.4) when exploiting Lemma 2.8 for a weight $(1/|\det DT^n|) \circ \kappa_i^{-1}$ (see also the comments before Corollary A.2). \square

APPENDIX A. OPERATORS \mathcal{M}_t AND \mathcal{L}_t

Theorem A.1.

- (1) *If the stable foliation of T is C^∞ then for any $p < 0$ and $s > 0$ with $q = s - p$ integer, there exists $t_1(q) > 1$ so that the essential spectral radius of \mathcal{L}_t on $W^{p,s-p,t}(\mathcal{X})$ is $\leq \rho_\infty^{(p,s)}(T)$, for each $1 < t < t_1$.*
- (2) *If the unstable foliation of T is C^∞ then for any $p < 0$ and $s > 0$ with $q = s - p$ integer there exists $t_2(q) \geq 1$ so that the essential spectral radius of \mathcal{M}_t on $W^{p,s-p,t}(\mathcal{X}, T^{-1})$ is $\leq \rho_\infty^{(-s,-p)}(T)$, for each $t_2 < t < \infty$.*

For any integer $q \geq 1$, there exist $C \geq 1$ and $t_1(q) > 1$ so that for every γ' with $1 \leq |\gamma'| \leq q$, all $1 \leq t < t_1$ and all $n \geq 1$, setting $h(x, y) = |\det DT^n|^{1/t} \circ \kappa_i^{-1}(x, y)$, then $|\partial_x^{\gamma'} h(x, y)| \leq Ch(x, y)$. (If $q = 1$ we may take $t_1 = \infty$.) Theorem A.1 is therefore a consequence of the following corollary of the proof of Lemma 2.10 combined with a refinement of the Leibniz formula for $a_{p,q}$ if $q \in \mathbb{Z}_+$, Lemma A.3.

Corollary A.2 (More on Lasota-Yorke). *There exist $\delta_0 > 0$ and C_0 so that, for all V with $\text{diam } V < \delta_0$ and $n \geq 1$, there exists $C(n) > 1$ so that for any multi-index γ' with $|\gamma'| \leq q$, any $f \in W^{p,q,t}$, compactly supported in U_j , and each C^∞ function $\Psi_{ij} : \mathbb{R}_i^d \rightarrow [0, 1]$ compactly supported in $U_{ij,n}$*

$$\begin{aligned} &\|\Psi_{ij} \cdot |\det DT^n \circ \kappa_i^{-1}|^{1/t} \cdot a_{p,0} \partial_x^{\gamma'} (f \circ T_{ij}^n)\|_{L^t} \\ &\leq C_0 \max((\lambda_{ij}(T^n))^p, (\nu_{ij}(T^n))^{q+p}) \|f\|_{p,q,t,\mathbb{R}_j^d} \\ &\quad + C(n) \|f\|_{p-1/2,q,t,\mathbb{R}_j^d}, \quad \forall p \leq 0, q \geq -p, 1 < t < \infty. \end{aligned}$$

Lemma A.3 (Leibniz formula for integer derivatives). *Let $1 < t < \infty$. Let $q \in \mathbb{Z}_+$ and let $p \in \mathbb{R}$. There exists $C \geq 1$, and for every*

compactly supported $h \in C^\infty(I^d)$ there exists $C(h) > 0$ so that for each $f \in W^{p,q,t}(\mathbb{R}^d)$, we have $a_{p,q}^{Op}(h \cdot f) = h \cdot a_{p,q}^{Op}(f) + g_1 + g_2$ with

$$\|g_1\|_{L^t} \leq C \sum_{\substack{|\gamma'|=q-1 \\ \gamma'_1+\gamma'_2=\gamma'}} \|\partial_x^{\gamma'_1} h \cdot a_{p,0}^{Op}(\partial_x^{\gamma'_2} f)\|_{L^t}, \quad \|g_2\|_{L^t} \leq C(h)\|f\|_{p-1,q,t}.$$

Proof. Decompose $a_{p,q}^{Op} = a_{p,0}^{Op} \circ a_{0,q}^{Op}$. The proof of Lemma 2.8 gives that if $\tilde{h} \in C^\infty(I^d)$ is compactly supported, then there is $C(\tilde{h}) \geq 0$ so that for all $\tilde{f} \in W^{p,0,t}(\mathbb{R}^d)$, we have $a_{p,0}^{Op}(\tilde{h} \cdot \tilde{f}) = \tilde{h} \cdot a_{p,0}^{Op}(\tilde{f}) + \tilde{g}$ with $\|\tilde{g}\|_{L^t} \leq C(\tilde{h})\|\tilde{f}\|_{p-1,0,t}$.

Since q is an integer, $a_{0,q}^{Op}(h \cdot f)$ decomposes as:

$$a_{0,q}^{Op}(h \cdot f) = \begin{cases} h \cdot f + \sum_{j=1}^{\ell} \binom{\ell}{j} (\partial_{x_1}^2 + \cdots + \partial_{x_{d_s}}^2)^j (h \cdot f) & \text{if } q = 2\ell \text{ is even,} \\ \mu_1 * a_{0,q-1}^{Op}(h \cdot f) + \mu_2 * \left(\sum_{j=1}^{d_s} R_{x_j} (\partial_{x_j} a_{0,q-1}^{Op}(h \cdot f)) \right) & \text{if } q = 2\ell + 1 \text{ is odd,} \end{cases}$$

where μ_1 and μ_2 are finite measures (which do not depend on h or f) and $*$ denotes convolution. Indeed, $q = 2\ell$ is even, just recall that $a_{0,q}^{Op} = (1 + \Delta_s)^{q/2} = (1 + \sum_{j=1}^{d_s} \partial_{x_j}^2)^\ell$. If $q = 2\ell + 1$, recall [18, V.3.2–V.3.4] that $(1 + \Delta_s)^{1/2}(\varphi) = \mu_1 * \varphi + \mu_2 * \left(\sum_{j=1}^{d_s} R_{x_j} (\partial_{x_j} \varphi) \right)$, where R_{x_j} is the Riesz transform [18, III.1]. Finally, use the ordinary Leibniz formula for partial derivatives, that $a_{p,0}^{Op}$ commutes with each R_{x_j} , that R_{x_j} is bounded on L^t , and that if μ is a measure, with total mass $|\mu|$, then $a_{p,0}(\mu * f) = \mu * a_{p,0}(f)$ and $\|\mu * f\|_{L^t} \leq |\mu| \cdot \|f\|_{L^t}$. \square

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